Nuclear Physics R&D at the U.S. Department of Energy Directed to Advanced Nuclear Fuel Cycles

Lee S. Schroeder

Presented at INPC 2010
Vancouver BC
July 4-9, 2010

LBNL and Tech Source Inc.

International Nuclear Physics Conference 2010 Vancouver INPC

Sunday July 4	Monday July 5	Tuesday July 6	Wednesday July 7	Thursday July 8	Friday July 9
	Registration	Registration	Registration	Registration	Registration
	Hot & Dense QCD	Nuclear Astrophysics	New Facilities and Instrumentation	Hadron Structure	SM tests & Fun Sym
	Break	Break	Break	Break	Break
	Hadrons in Nuclei	Nuclear Reactions	Applications and Interdisciplinary Research Award Session	Nuclear Structure	Neutrinos and Nuclei Closing Remarks
	Lunch (on own)	Lunch (on own) Lunchtime Seminars	Lunch (on own)	Lunch (on own) Lunchtime Seminars	End of conference
Registration Reception Chan Centre	Parallel Sessions South Campus	Parallel Sessions South Campus	Excursion	Parallel Sessions South Campus	
Public Lecture Chan Centre	Break	Break		Break	TRIUMF tour
	Poster Session LSC Atrium	Poster Session LSC Atrium		Banquet	

LBNL and Tech Source Inc.

January 27, 2010: President Obama's State of the Union Speech

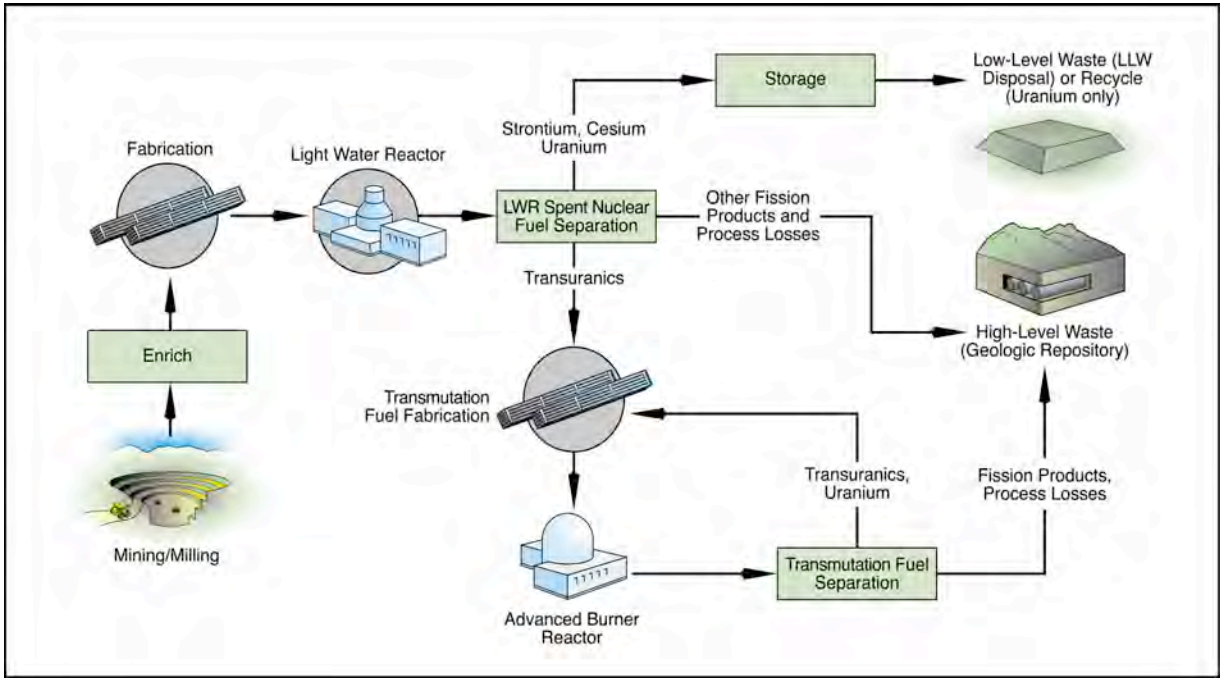
"But to create more of these clean energy jobs, we need more production, more efficiency, more incentives. And that means building a new generation of safe, clean nuclear power plants in this country."

LBNL and Tech Source Inc.

Outline

- **Recent History of Advanced Nuclear Fuel Cycles at U.S. DOE NE**
  - AFCI
  - GNEP
    - Campaigns + Pilot Plants + SFR
    - Current Science-Based R&D
- **Key Elements of Recent NE Roadmap**
- **Role of Modeling and Simulation**
- **Examples of FC R&D Activities**
- **Future Directions**
  - Interactions within DOE (particularly with Office of Science)

Opportunities Within Advanced Fuel Cycles (AFC)



Overview of possible nuclear fuel cycle

Elements of AFC: Mining fissile material

Enrichment and fabrication of reactor fuel

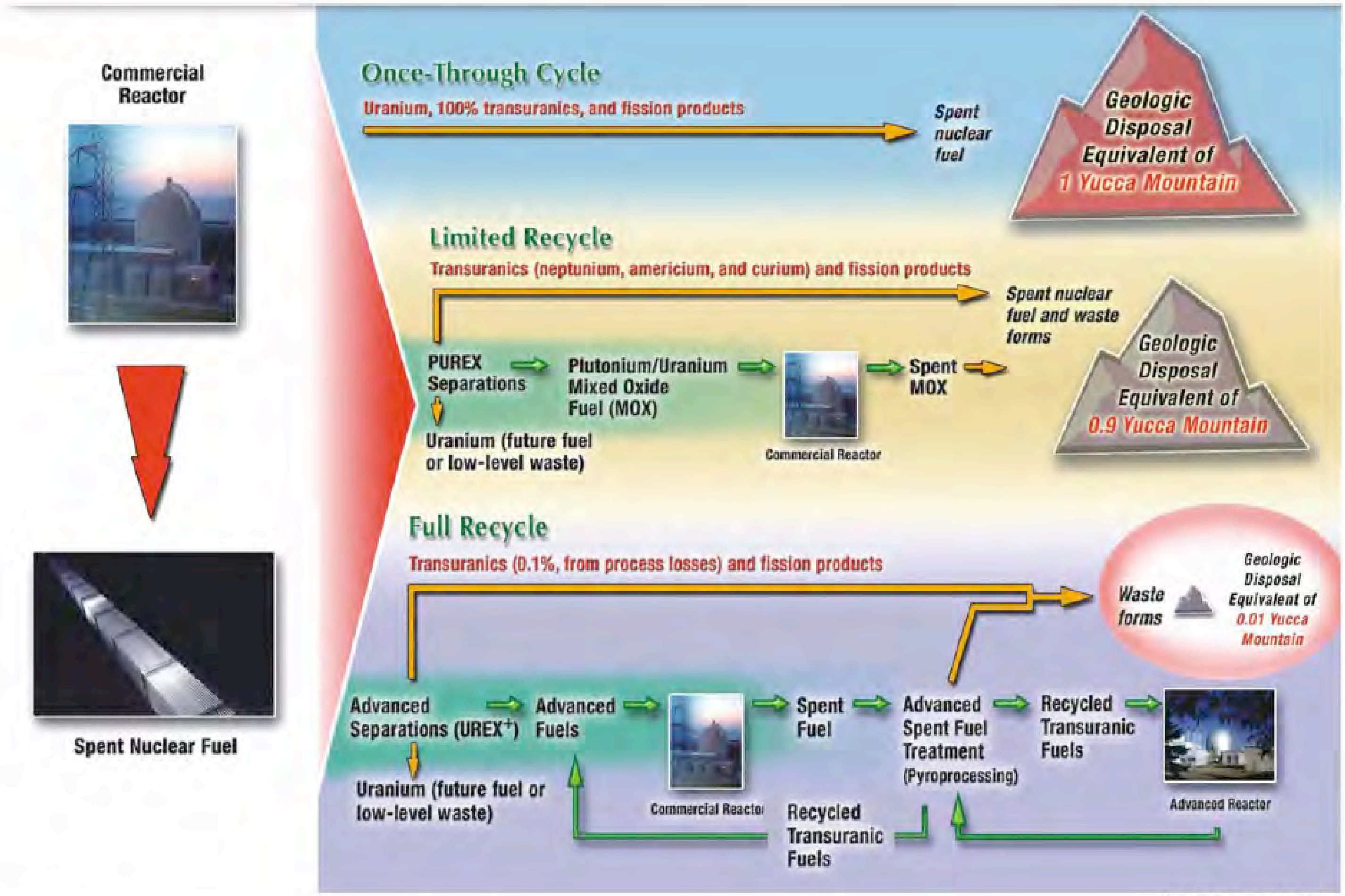
Burning fuel in reactor

Separation of spent nuclear fuel

Storage in repository

GNEP

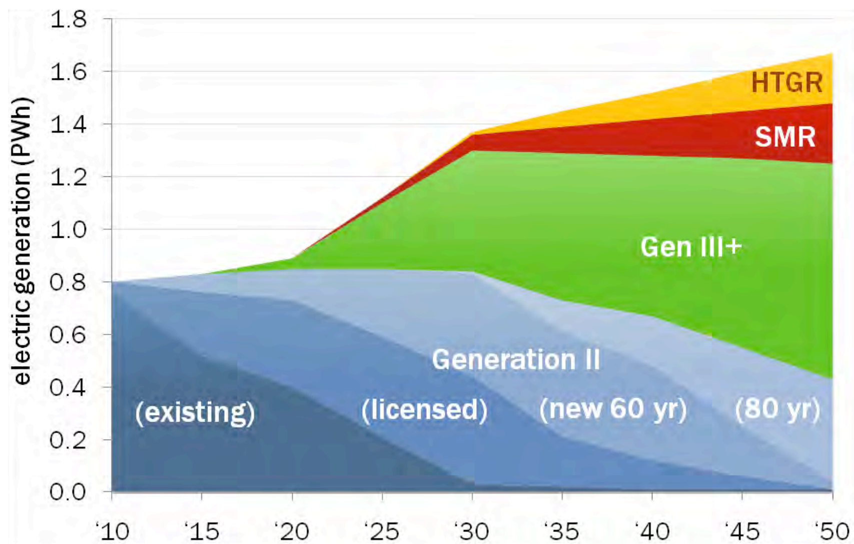
Domestic Used Nuclear Fuel Management Options



Source: Finck (ANL)

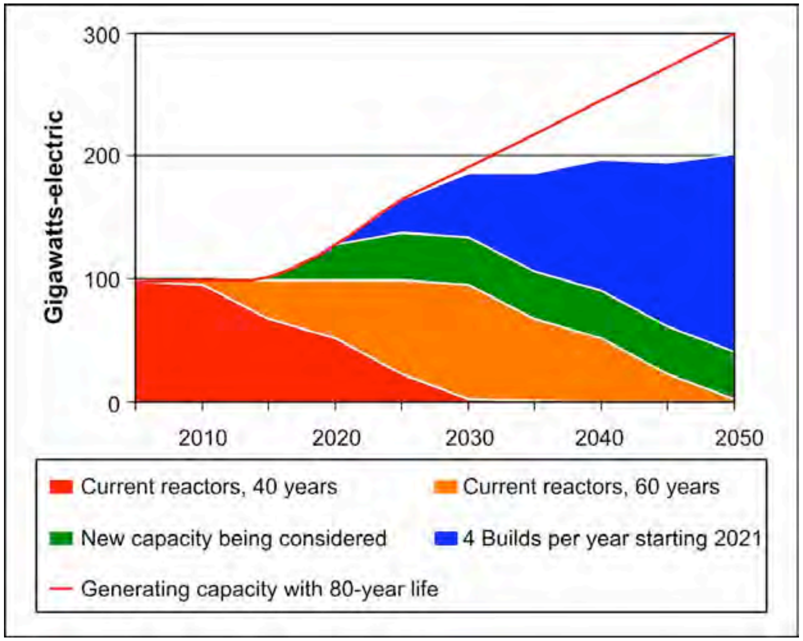
Four Nuclear Energy Objectives

- Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.
- Develop sustainable fuel cycles.
- Understanding and minimizing the risks of nuclear proliferation and terrorism.



R&D Objective 1: Life Extension

- **Goal is to extend plant life beyond 60 years with improved performance.**
- **Challenges facing current fleet**
  - Aging and degradation of system structures and components
  - Fuel reliability and performance
  - Obsolete analog instrumentation and control technologies
  - Design and safety analysis tools based on 1980's vintage knowledge bases and computational capabilities.



- **Necessary R&D**
  - Nuclear Materials Aging and Degradation
  - Advanced LWR Nuclear Fuel Development
  - Advanced Instrumentation, Information, and Control Systems Technologies
  - Risk-Informed Safety Margin Characterization
  - Economics and Efficiency Improvement

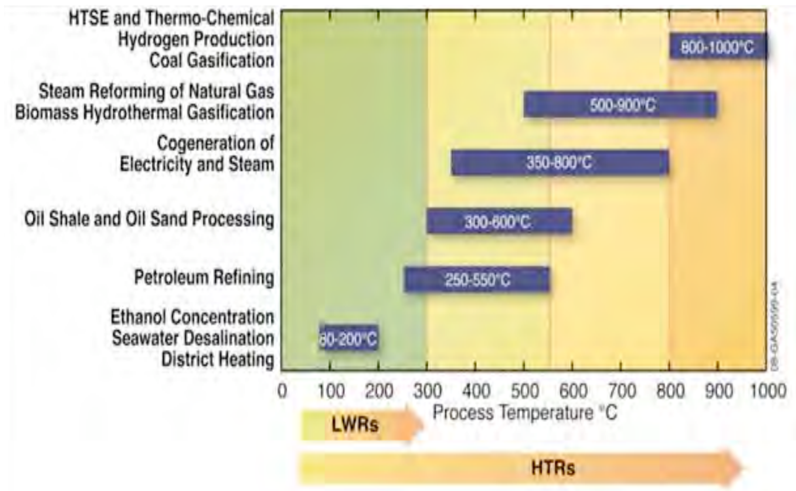
R&D Objective 2: New Builds

- **Goals are:**
  - Demonstrate 10 CFR Part 52 licensing framework
  - Facilitate accelerated licensing of small modular reactors
  - Facilitate the development and demonstration of advanced manufacturing and construction technologies
  - Develop and demonstrate next generation advanced plant concepts and technologies

- **Necessary R&D**
  - Address required changes to current licensing frameworks to accommodate new technologies and designs
  - Enable new technology insertion into emerging and future designs
  - Innovative concepts and advanced technologies
  - Fundamental phenomena and performance data
  - Advanced modeling and simulation capabilities
  - New technology testing and demonstration
  - Advanced manufacturing and construction technologies

Imperative 3: Transition Away From Fossil Fuels (Now part of R&D Objective #2)

- **Challenges**
  - Providing process heat to industry will require
    - Higher temperature reactors
    - Efficient heat transport systems
    - Interface systems for control and isolation
    - Development of a robust licensing case
  - Institutional differences between transportation, industrial, and electric power sectors
  - Use of high temperature reactors will generate used fuels that are not in the present fuel cycle



- **Necessary R&D**
  - Develop reactors of the appropriate size and outlet temperature
  - Develop associated fuels, graphite and high temperature structural materials
  - Develop heat transfer and interface systems
  - Develop energy conversion technologies
  - Develop modeling and simulation capabilities to evaluate interactions between reactors and the chemical plants or refineries which they would serve

R&D Objective 3: Sustainable Fuel Cycles

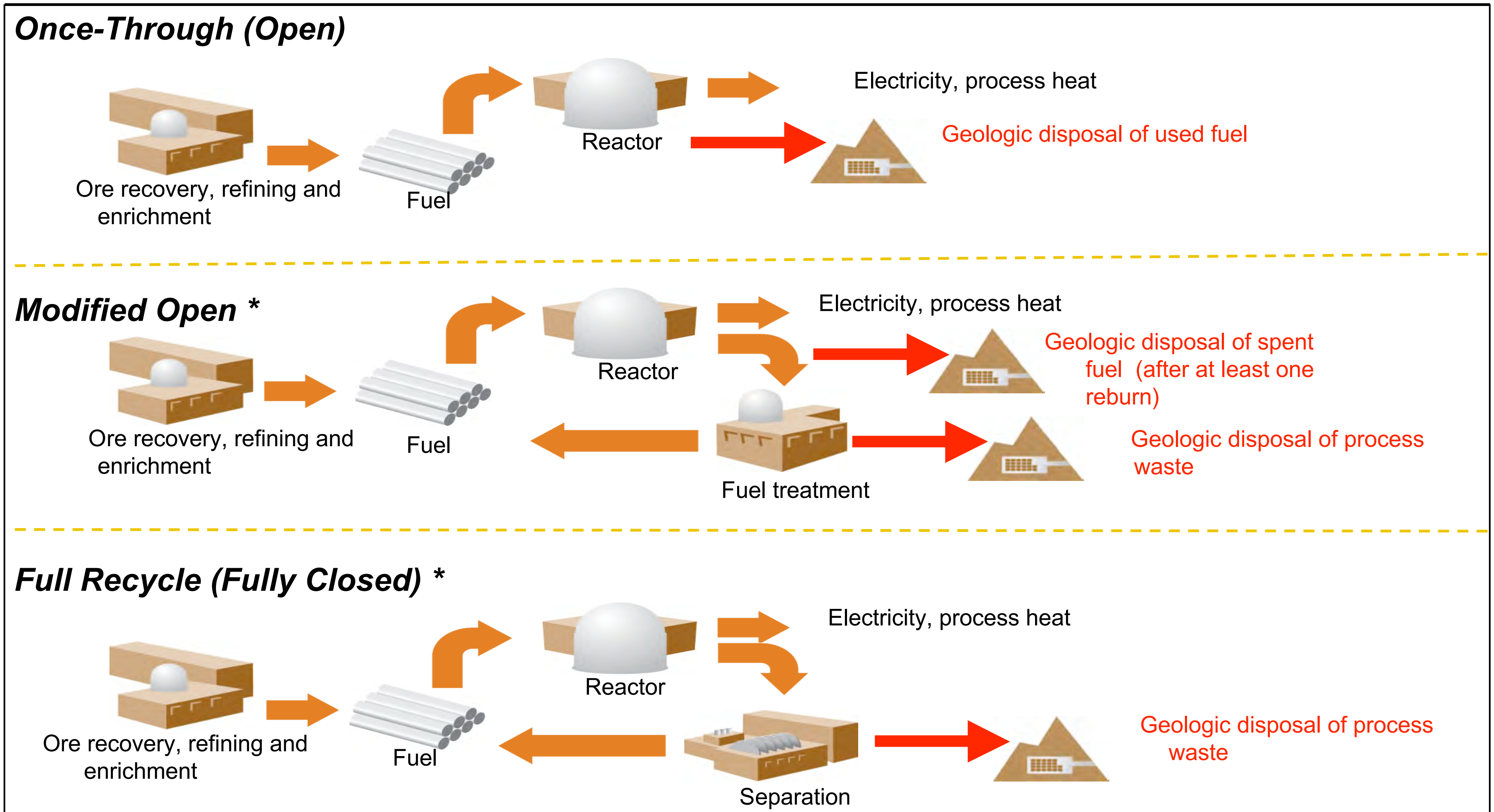
Objectives

- In the near term, define and analyze fuel cycle technologies to develop options that increase the sustainability of nuclear energy
- In the medium term, select the preferred fuel cycle option(s) for further development
- By 2050, complete demonstration of the selected fuel cycle options at engineering scale and be ready to turn over to industry for commercialization

Necessary R&D

- Reduce transuranic production
- Implement science-based development program for fuel recycling
- Obtain mechanistic understanding of waste form behavior
- Perform fundamental analysis of fuel fabrication processes, and fuel/clad performance
- Evaluate very high burnup systems that require minimal or no chemical separations
- Develop transmutation systems needed to supplement partial recycling in thermal reactors
- Enable real time nuclear material accountancy and control
- Analyze storage and disposal system performance in a variety of environments

Three Potential Fuel Cycle Options



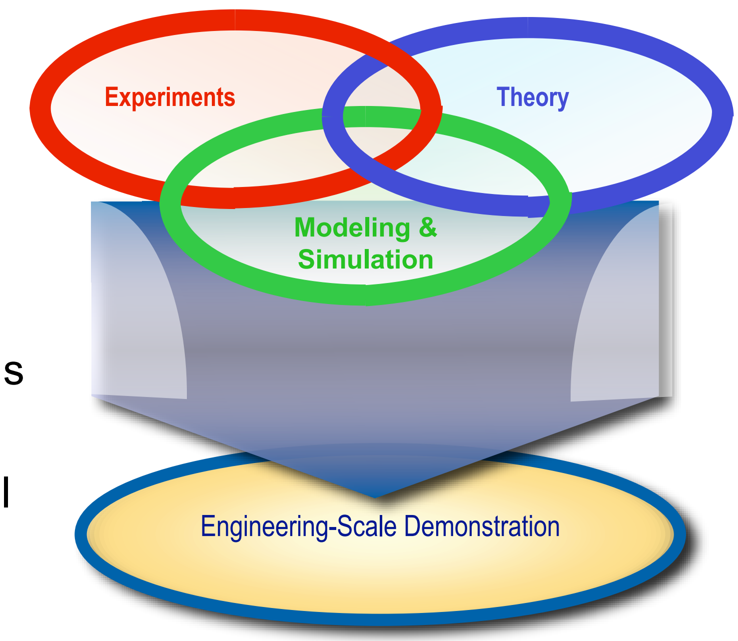
*A specific fuel cycle strategy may include more than one fuel design, reactor design, or fuel treatment process.

R&D Objective 4: Understand and Minimize Risk of Proliferation and Terrorism

- **Limiting proliferation and security threats requires protecting materials, facilities, sensitive technologies and expertise**
- **Challenges**
  - Development of proliferation risk assessment methodologies and tools
  - Minimizing the potential for misuse of technology and materials
  - Development of highly reliable, remote, and unattended monitoring technologies
  - Designing improved safeguards into new energy systems and fuel cycle facilities
  - Development of advanced material tracking methodologies
- **Necessary R&D**
  - Development of approaches that minimize enrichment facilities
  - Development of fuels that produce less attractive materials
  - Development of intrinsically safe, secure, and safeguardable reactor systems
  - Development of cost-effective options that produce less attractive material streams
  - Development of fabrication, storage, and transportation approaches with safeguards and security benefits

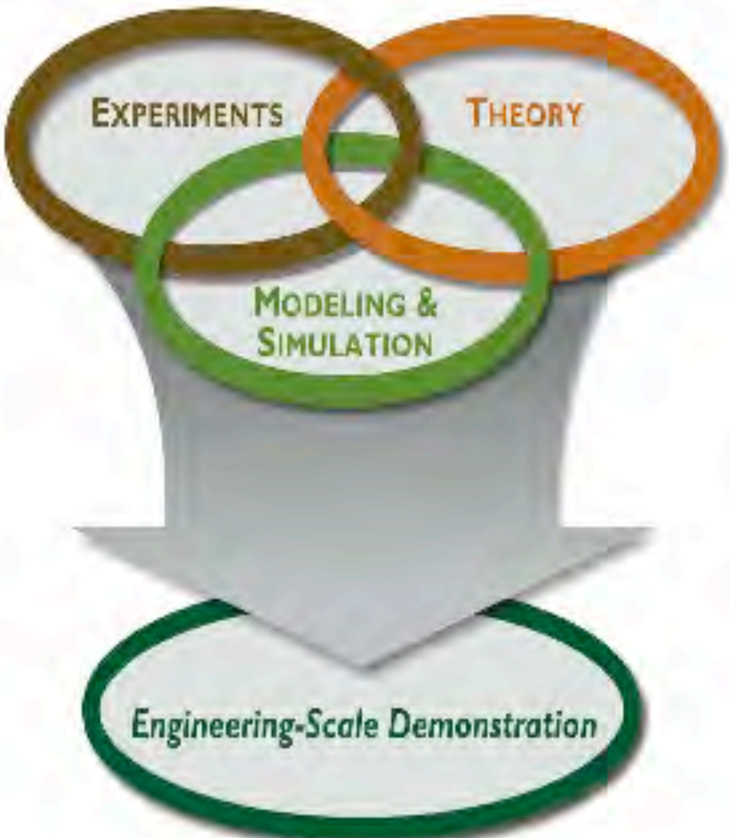
Science Based Approach to Nuclear Energy Development

- ***Experiments*** – Physical tests done to develop understanding of single effects or integrated system behaviors.
- ***Theory*** – Creation of models (i.e. theories) of physical behaviors based on understanding of fundamental scientific principals and/or experimental observations.
- ***Modeling and Simulation*** – Use of computational models to develop scientific understanding of the physical behaviors of systems. Also used to apply scientific understanding to predict the behavior of complex physical systems.
- ***Demonstrations*** – New technologies, regulatory frameworks, and business models integrated into first-of-kind system demonstrations that provide top-level validation of integrated system technical and financial performance.



Advanced Modeling and Simulation has become an Essential Part of NE R&D

U.S. DEPARTMENT OF ENERGY
Nuclear Energy



- ***R&D Objective 1*** – Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- ***R&D Objective 2*** – Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.
- ***R&D Objective 3*** – Develop sustainable nuclear fuel cycles.
- ***R&D Objective 4*** – Understand and minimize the risks of nuclear proliferation and terrorism.

Recent Comments from Steven E. Kooning
U.S. DOE Under Secretary for Science
June 14, 2010
SF Chronicle, page A-10

"Supercomputers enable simulation - that is, the numerical computations to understand and predict the behavior of scientifically or technologically important systems - and therefore accelerate the pace of innovation. Simulation enables better and more rapid product design. . . . Simulation also accelerates the progress of technologies from laboratory to application."

"We in the Department of Energy have not been sitting idle. The Nuclear Energy Simulation Hub at Oak Ridge National Laboratory has just been established. This hub is a collaboration of national laboratories, industry and universities."

Leadership Computing Facilities

The Office of Science leads the World in supercomputing capabilities

"Supercomputer modeling and simulation are changing the face of science and sharpening America's competitive edge."

Secretary Steven Chu

The Cray XT5 Supercomputer at Oak Ridge National Lab can perform over 2.3 quadrillion operations per second. It ranks #1 of the fastest computers world wide by Top500.org

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Nuclear Energy Can Benefit from Modeling and Simulation in the Near, Mid, and Long Terms

Nuclear Energy Issues

Time (* Dates Approximate)

2010 — 2020 — 2040

Power Uprates

Higher Burnups

Deployment of Gen III+ Reactors

NGNP

Small Modular Reactors

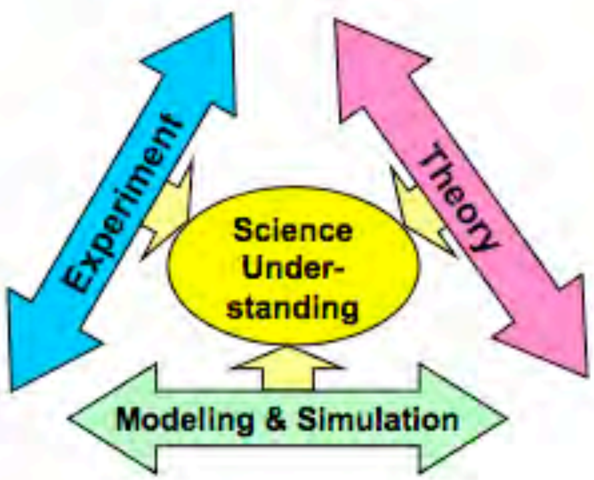
License Extensions

Gen IV Reactors

Waste Repository

Closed Fuel Cycle

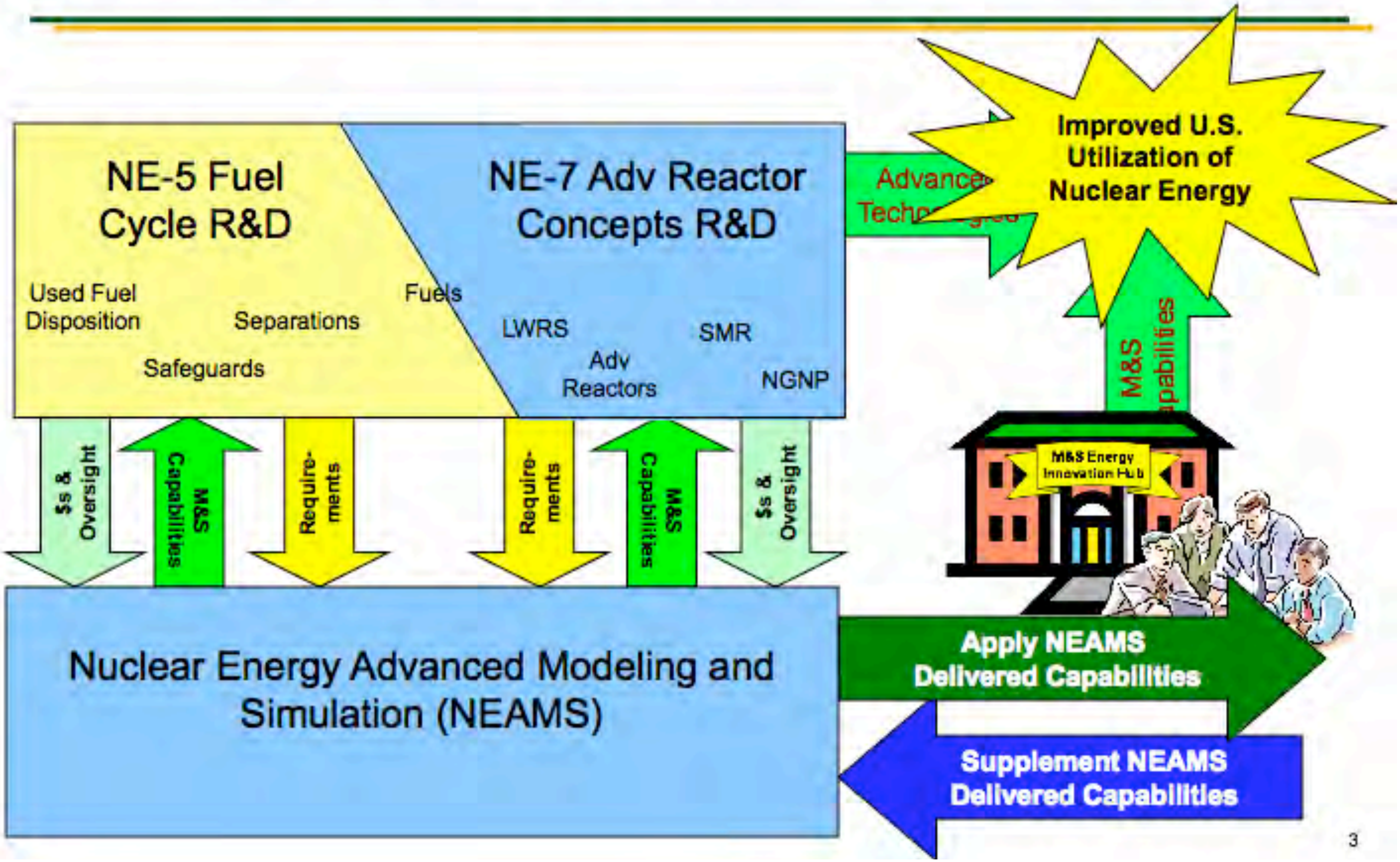
Near-Term — Mid-Term — Long-Term



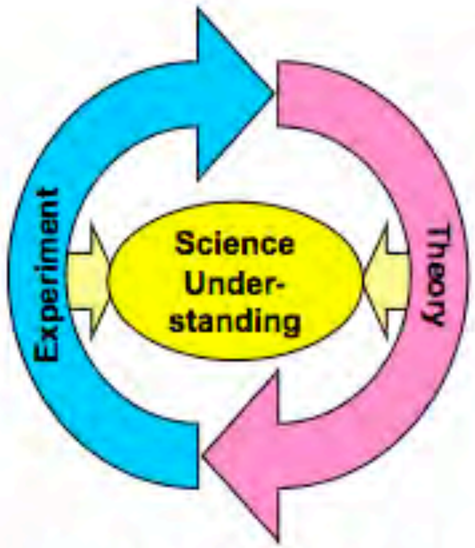
New means of improved understanding nuclear energy Issues

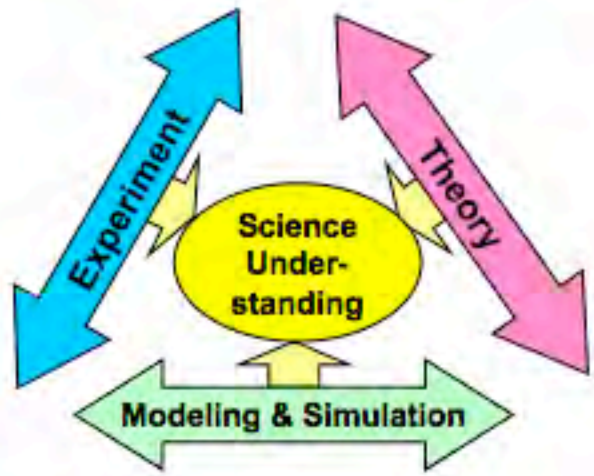
Modeling and simulation has become a peer to theory and experiment to develop science insight

NEAMS and the Energy Innovation Hub Will Play Important Roles



Enabling a Shift to a Modern Science Based Approach

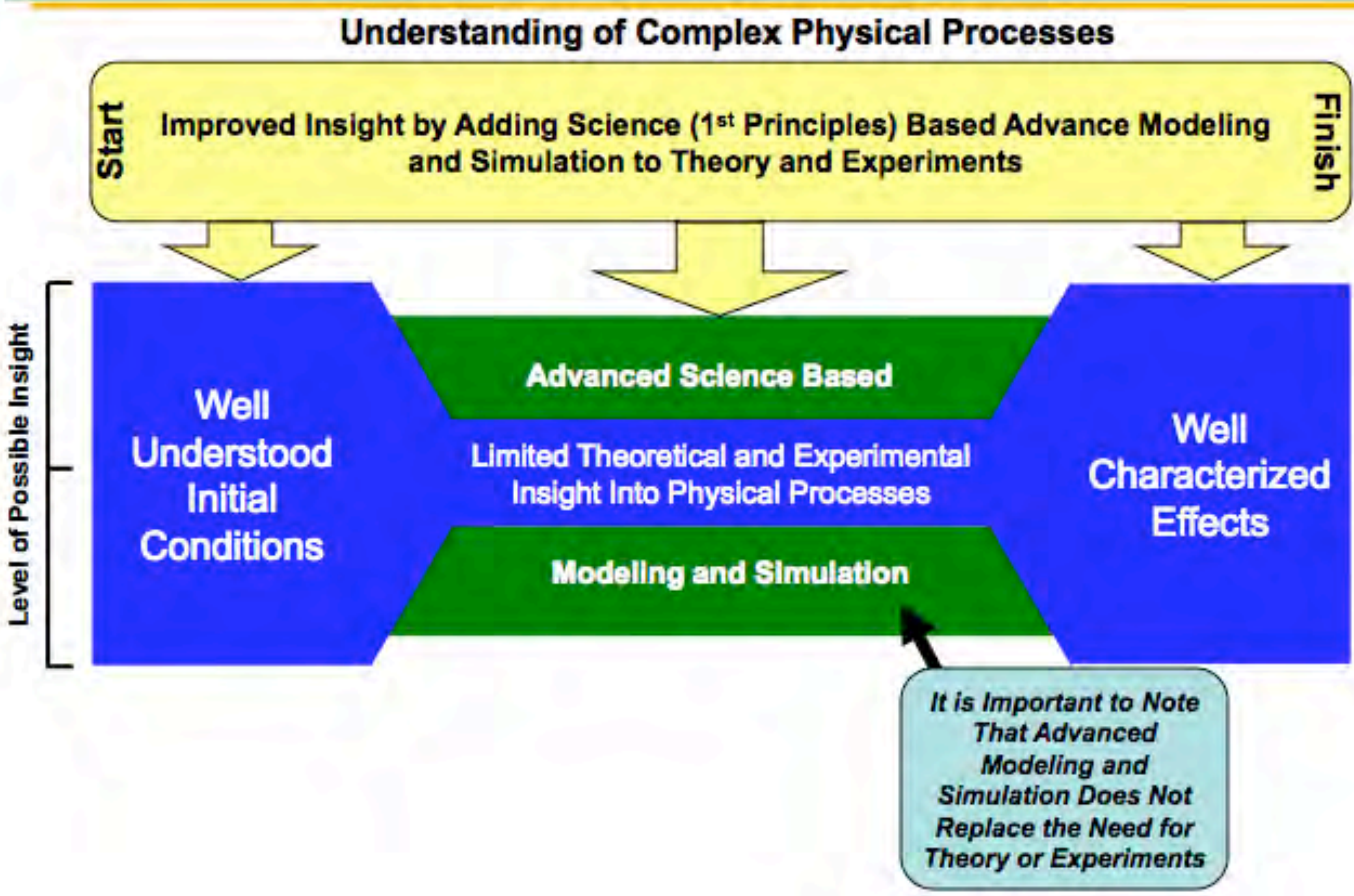




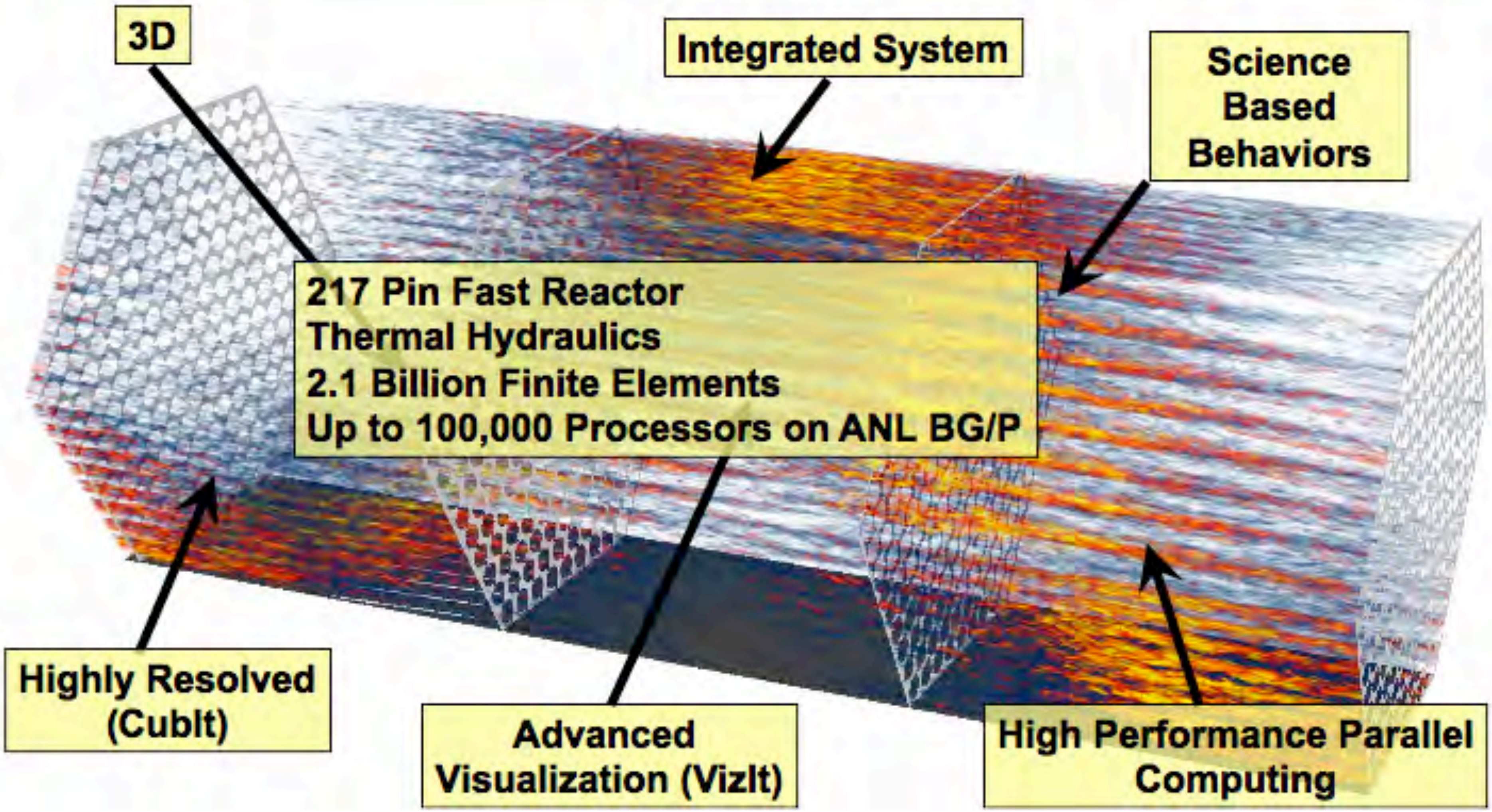
- **Traditional Science Approach**
  - Theory drives design of Experiments
  - Experiments provides discoveries to drive Theory
  - Empirically based modeling and simulation heavily dependent on staying close to experimental basis

- **Addition of Science Based Modeling and Simulation**
  - Science (1st principles) based modeling and simulation used to extrapolate and predict beyond tested states
  - Can quickly confirm or disprove Theory hypotheses
  - Improve experiments by predicting "areas of interest" and expected results

Supplements Theory and Experiment to Explain "How" Things Happened



What Does Simulation for Discovery Look Like?



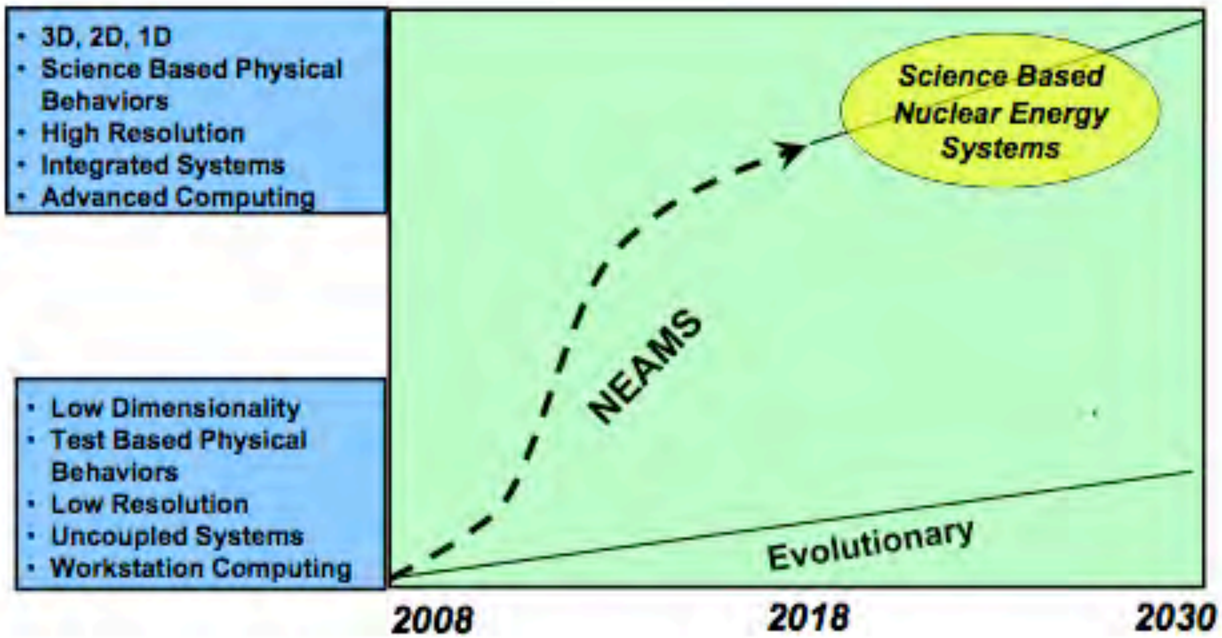
Nuclear Energy Advanced Modeling and Simulation (NEAMS)

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Vision

To rapidly create and deploy "science-based" verified and validated modeling and simulation capabilities essential for the design, implementation, and operation of future nuclear energy systems with the goal of improving U.S. energy security



U.S. DEPARTMENT OF ENERGY

Nuclear Energy

NEAMS Has Assembled the "A" Team of Labs, Universities and Industry

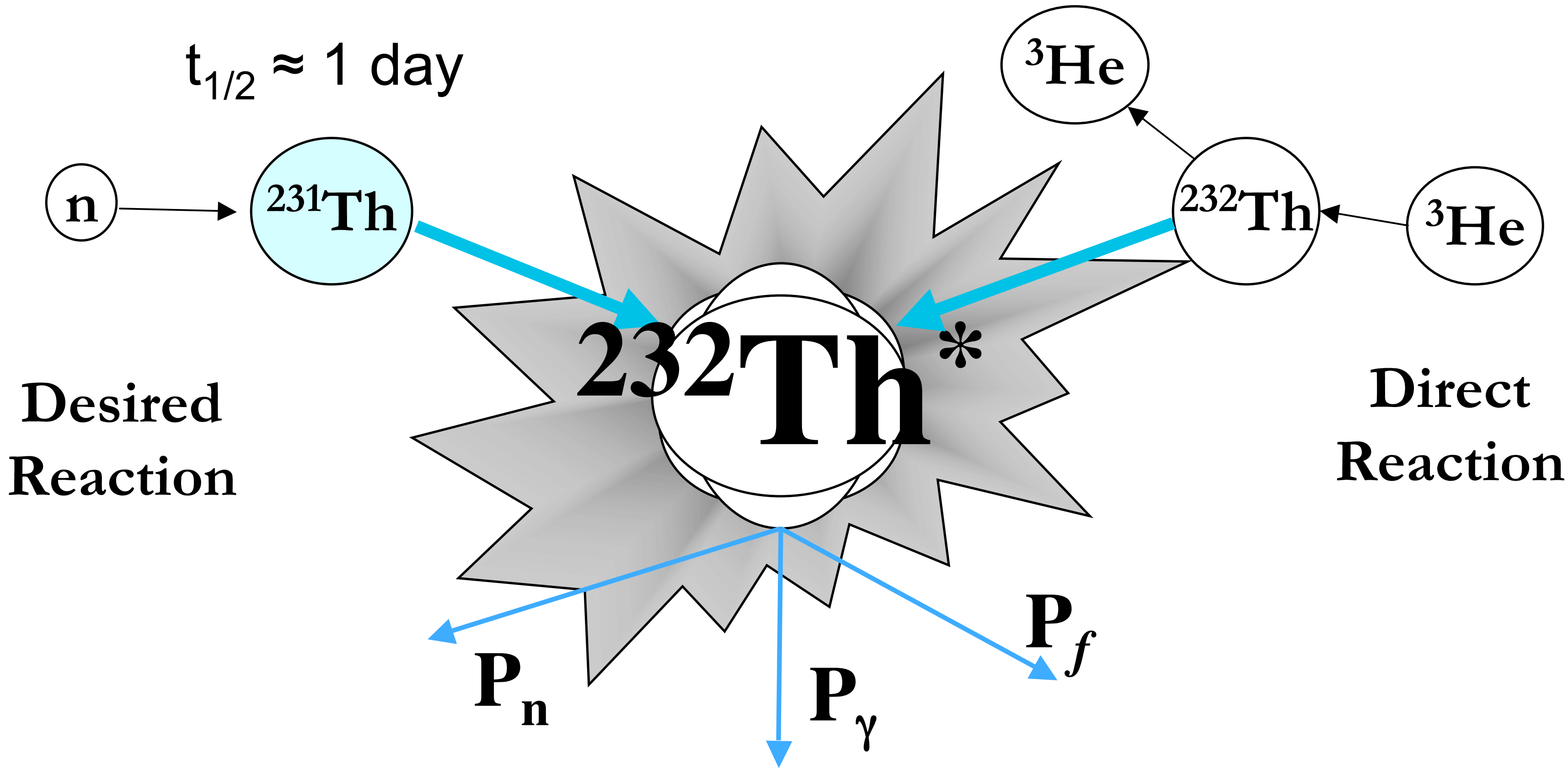
- **Integrated Performance and Safety Codes**
  - Nuclear Fuels
    - LANL – lead
    - ORNL
    - LLNL
    - INL
    - Texas A&M
    - UC Davis
    - Oklahoma State
  - Reactors
    - ANL – lead
  - SafeSeps
    - LANL – lead
    - ORNL
    - ANL
    - SUNY Stonybrook
  - Waste
    - SNL – lead
    - LBNL
    - ANL

- **Supporting Program Elements**
  - Fundamental Methods and Models
    - PNNL – lead
    - SNL
    - ORNL
    - North Carolina State
    - Michigan
    - Nevada, Reno
    - Wisconsin
  - Verification, Validation and Uncertainty Quantification
    - INL – lead
    - SNL
    - LANL
    - University of Idaho
  - Capability Transfer
    - ORNL
    - ANL
    - IBM
  - Enabling Computational Technologies
    - LLNL

Examples of Fuel Cycle R&D

- Surrogate Reactions
- LANSCE TPC
- Pb Slowing Down Spectrometer (from Oct. '09 FCR&D meeting)
- ATR as national user facility (from Jan. '10 APS Workshop at ANL)
- UMLV
  - Elements of program
  - Rad-chem summer school (in session now)
- NNDC — data analysis (co-variance)
- Others? List activities? List of University Groups?
- IAC activities

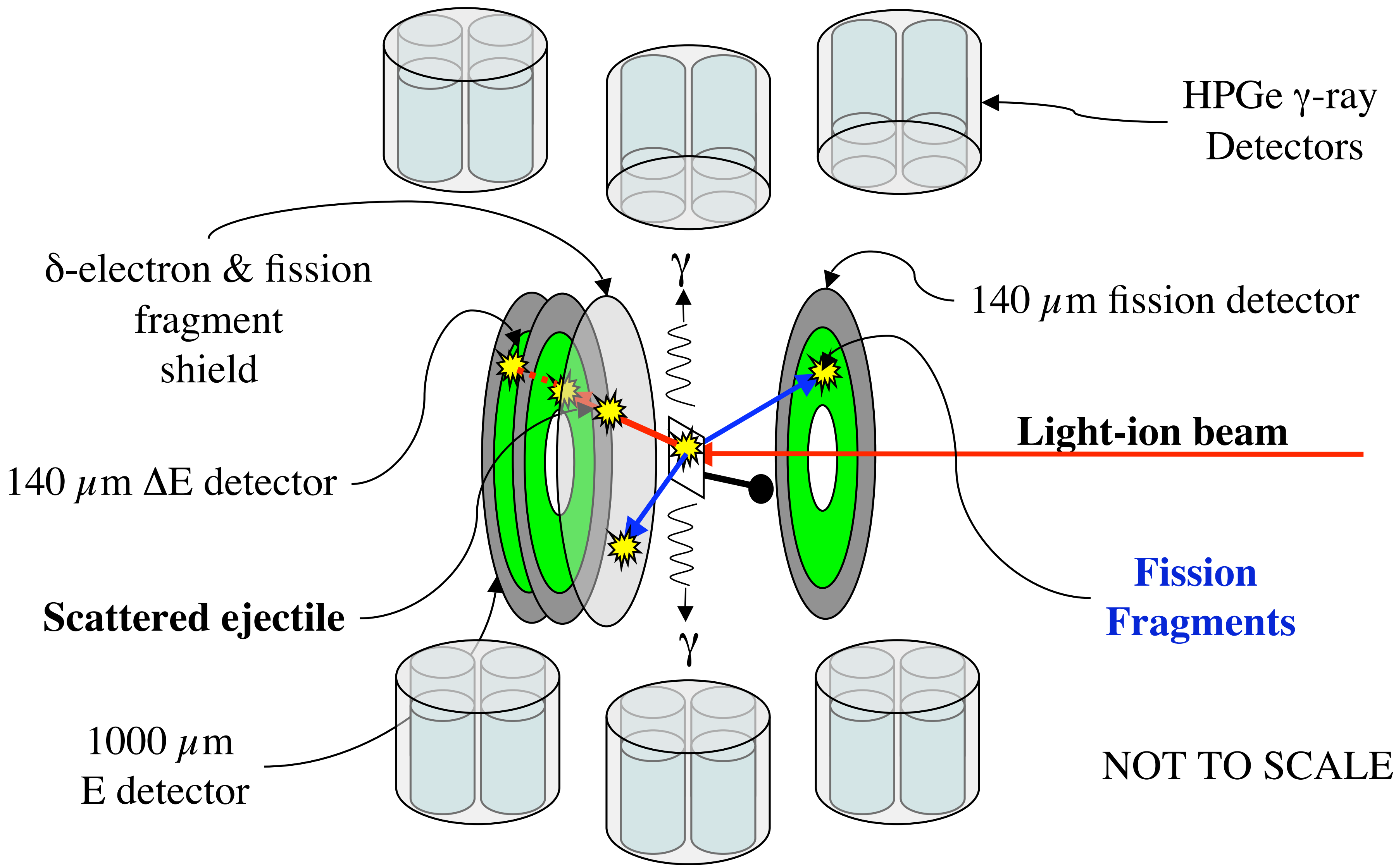
The Surrogate Ratio Method



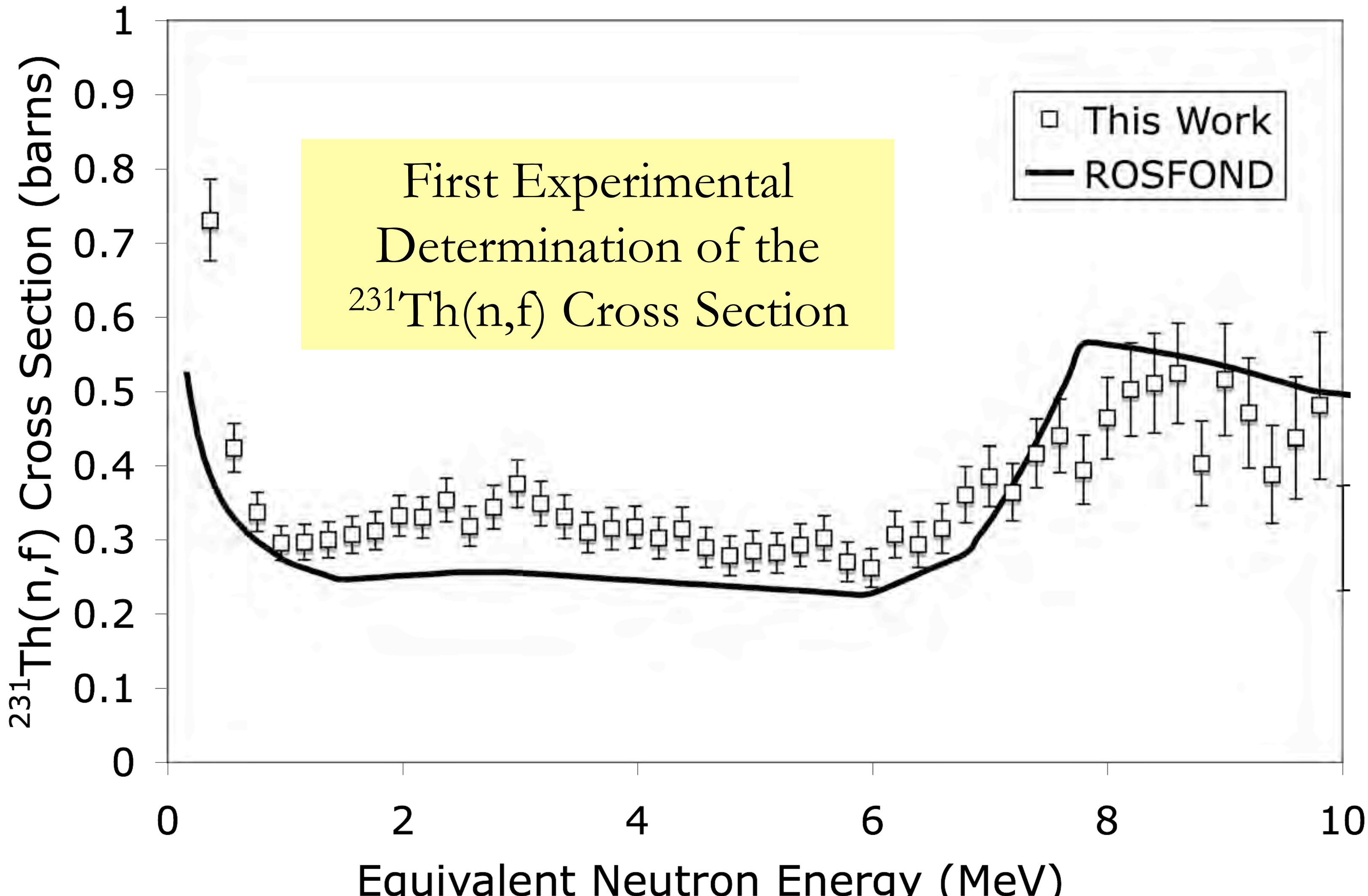
^{232}Th(^{3}He,^{3}He'f) → ^{232}Th* ← ^{231}Th(n,f)

^{236}U(^{3}He,^{3}He'f) → ^{236}U* ← ^{235}U(n,f)

Silicon Telescope Array for Reaction Studies (STARS) Experimental Schematic



Applications in Nuclear Security and Advanced Nuclear Reactor Design



B.L. Goldblum, *et al.* Phys. Rev. C **80**, 044610 (2009).

THE SRM Collaboration

L.A. Bernstein, D.L. Bleuel, J.T. Burke, L. Ahle, J. Escher, F.S. Dietrich, S.L. Lesher, K. Moody, N. Scielzo, I. Thompson, M. Wiedeking, W. Younes

L. Phair, M.S. Basunia, P. Fallon, R.M. Clark, M.A. Delaplanque-Stephens, I.Y. Lee, A.O. Macchiavelli, F.S. Stephens

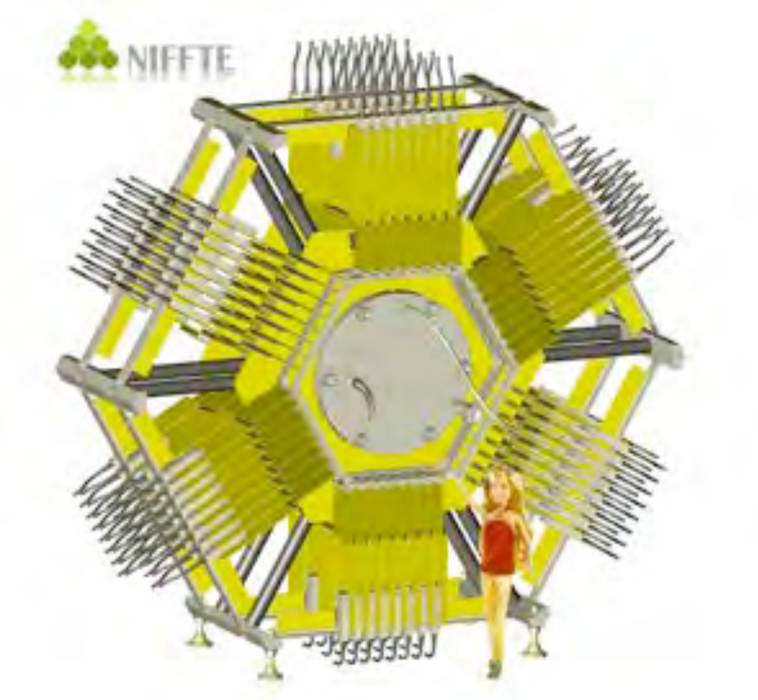
K. Alfonso, K. Evans, L.G. Moretto, B.L. Goldblum, E.B. Norman, S.G. Prussin, R. Stroberg, E. Swanberg

M. Guttormsen

C.W. Beausang, B. Crider, J.M. Allmond, B. Darakchieva, M. Evtimova

R. Hatarik, J. Cizewski

An Innovative Approach to Precision Fission Measurements Using a Time Projection Chamber



Project Work Scope

- **Create groundwork and infrastructure for a successful fission cross section measurement campaign**
  - Fission ratio measurements for $^{239}Pu/^{235}U$ and $^{238}U/^{235}U$
  - Create design proposal to measure the ratio $^{235}U/H(n,n)H$ to provide the best single measurement of the ^{235}U fission cross section
    - Convert any subsequent ratio experiments to the best absolute measurements available.
- **Design and build a TPC and develop the requisite online, offline and FPGA software to conduct a fission cross sections measurement**

Advancing the nuclear fuel cycle requires improvements in basic nuclear data

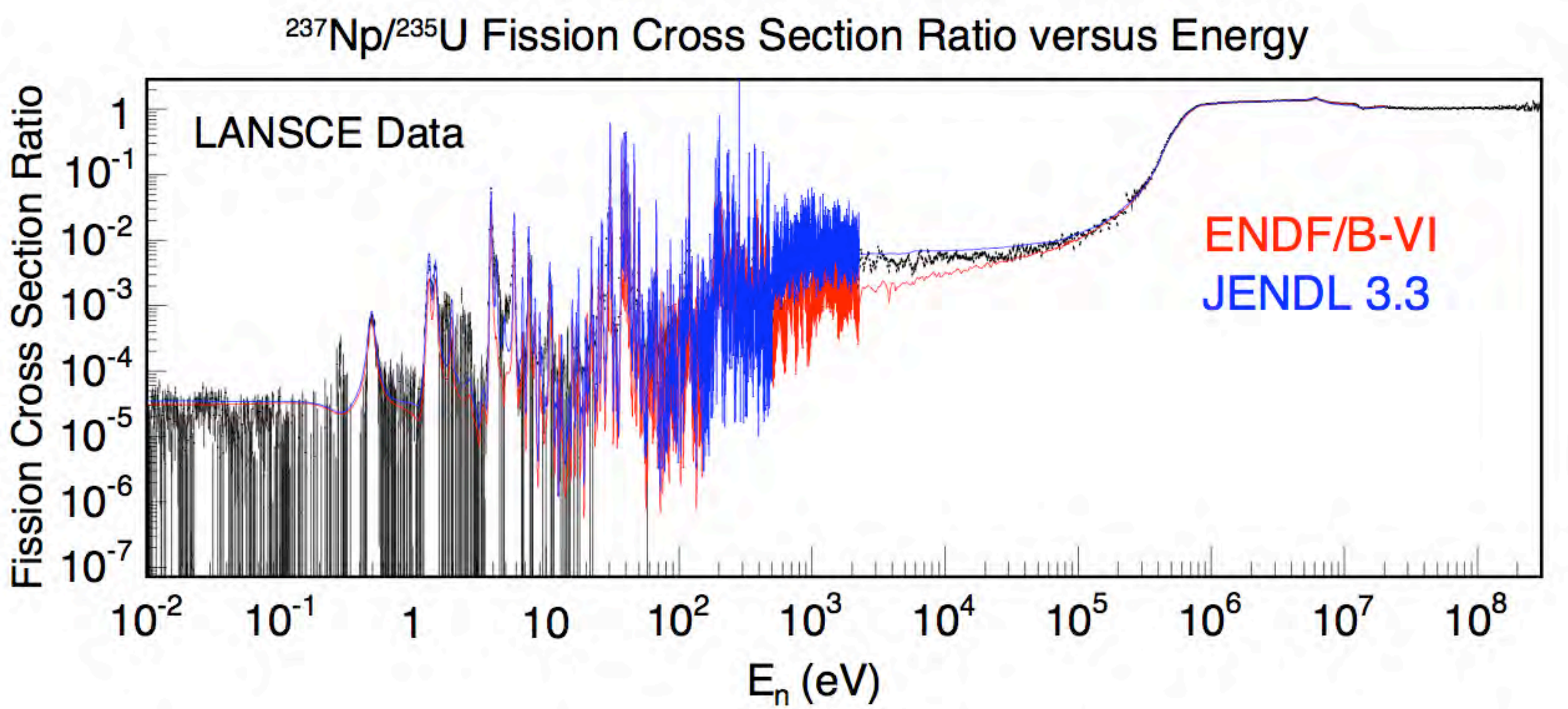
- **Nuclear data plays an important role in the calculations performed in most of the GNEP campaigns and cross-cutting activities**
  - Reactor core and fuel design
  - Safety parameter assessment
  - Criticality safety
  - Shielding
  - Material damage in structures
  - Decay heat at reactor shutdown
  - Decay heat in the repository
  - Mass flow in the fuel cycle
  - Material detection

There are broad needs for nuclear data in the advanced fuel cycle.

Need for the Fission TPC

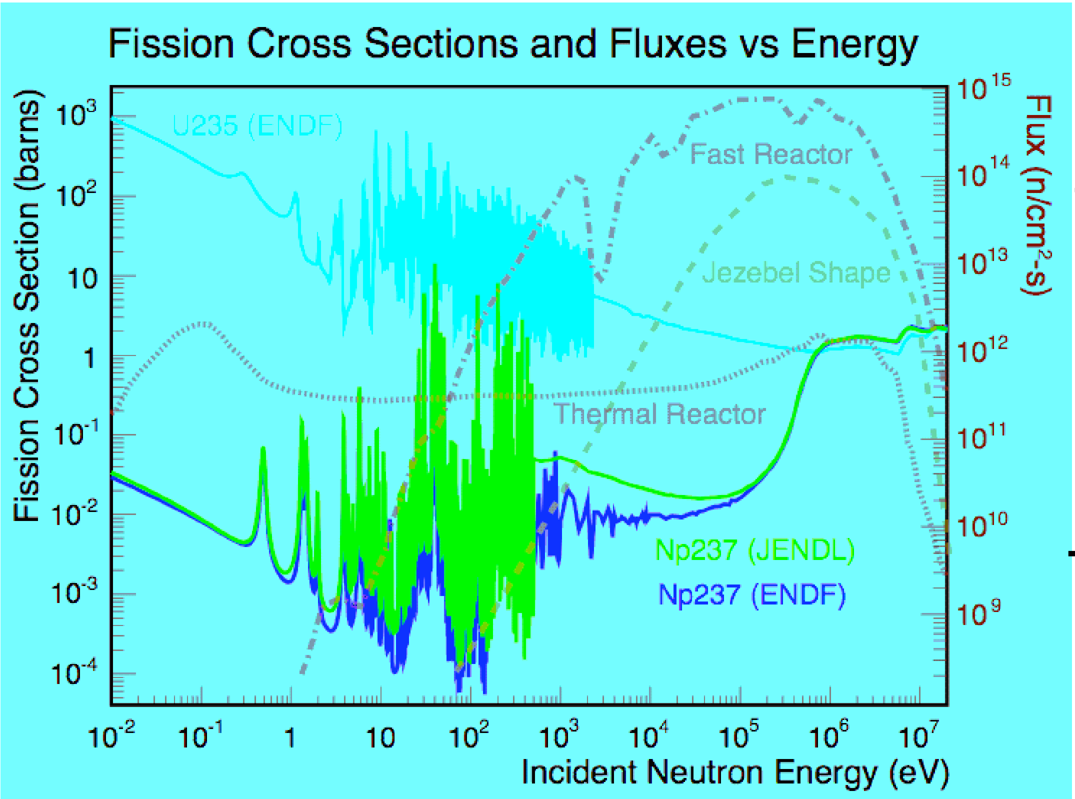
- **Nuclear data libraries are prepared that include what is considered the best estimates to nuclear quantities of interest**
  - The libraries are a culmination of nuclear theory and experiments
  - There are a variety of nuclear data libraries
    - ENDF (USA)
    - JENDL (Japan)
    - JEFF (Europe)
    - BRONDL (Russian)
    - And there are others, and they all have discrepancies in comparison
- **Uncertainties in the nuclear data libraries propagate to uncertainties in calculated integral quantities, driving margins and costs in advanced system designs**

The fast region contains a number of discrepant cross sections, Np-237 is a good example



Until a recent precision measurement funded by GNEP, the Np-237 fission cross section in the fast region was questionable

Fast Reactor Data Needs Are Different From Those Of The Thermal Reactor



Neutron flux shapes folded with cross sections determines the region of interest (both energy and isotopes).

The magnitude of the neutron flux drives cross section uncertainty requirements

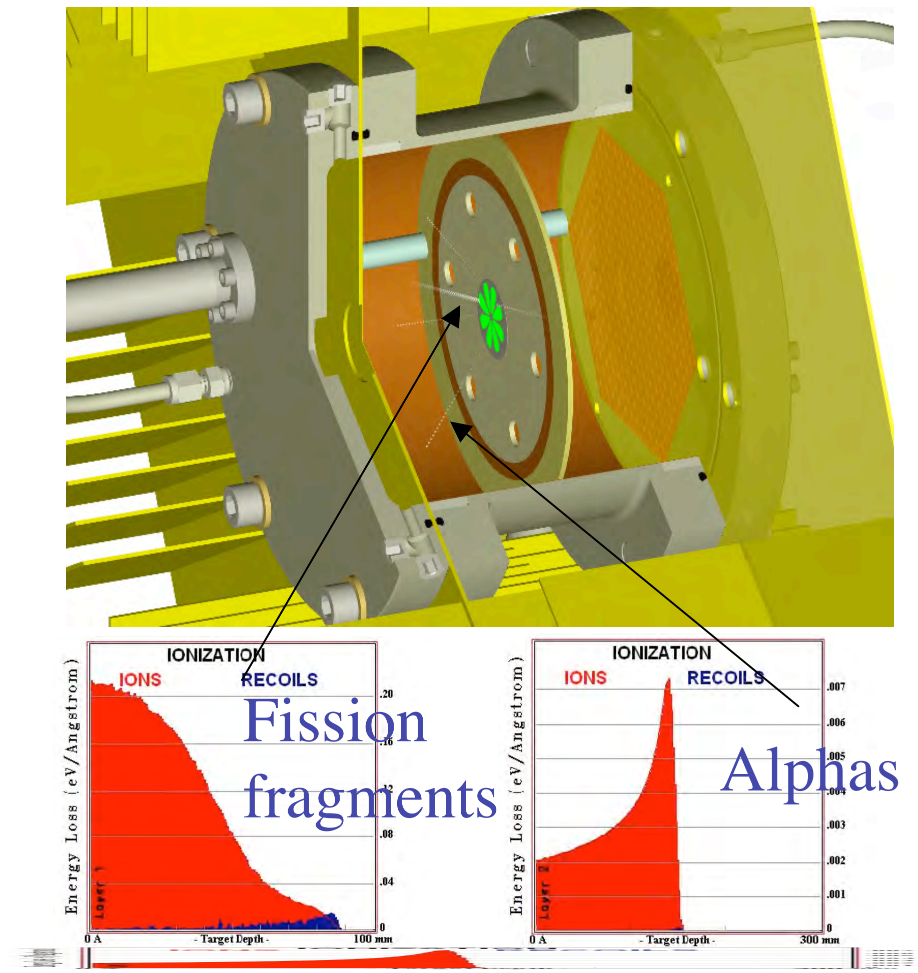
Reactor sensitivity studies identify and quantify ABR nuclear data needs

- **Uncertainties in basic nuclear data lead to uncertainties in calculations of:**
  - Criticality (multiplication factor)
  - Doppler Reactivity Coefficient
  - Coolant Void Reactivity Coefficient
  - Effective Delayed Neutron Fraction
  - Reactivity Loss during Irradiation
  - Transmutation Potential
  - Peak Power Value
  - Reactivity Control
  - Decay Heat
  - Radiation Source at Fuel Discharge Radiotoxicity
  - Neutron reactor spectra
  - And more

Nuclear Data Sensitivity studies reveal liabilities in the nuclear data that FC R&D needs to address

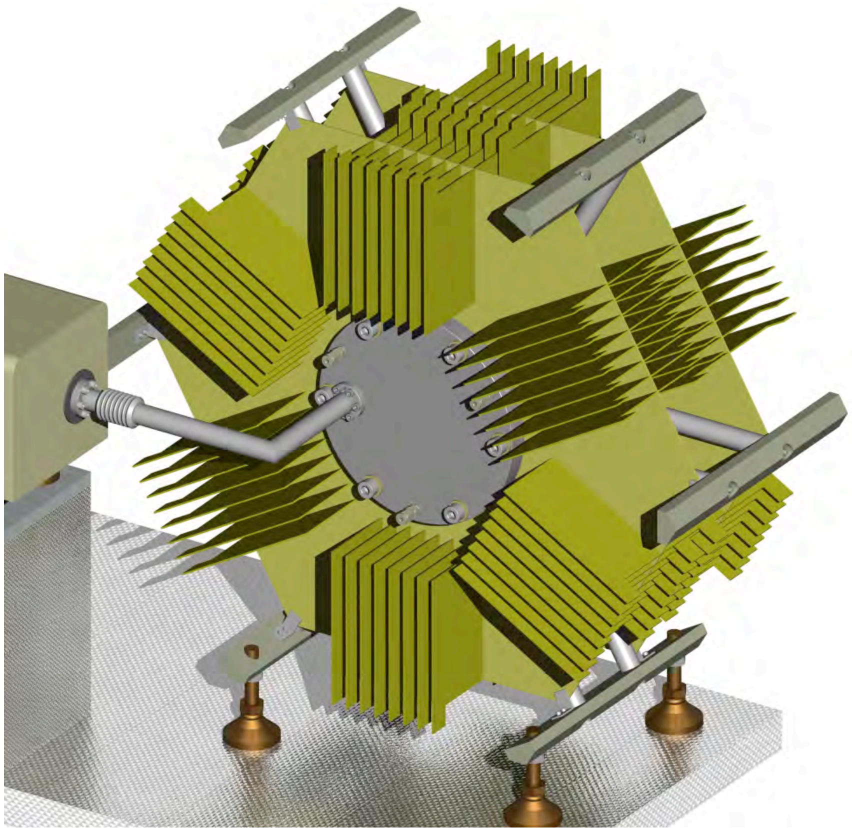
A Time Projection Chamber (TPC) To Provide Unprecedented Fission Cross Section Measurements

- **Sub-percent fission measurements will significantly reduce uncertainties that impact reactor and fuel cycle integral quantities**
- **TPC will provide 3D “pictures” of the charged particle trajectories**
  - Alpha backgrounds removed
  - Sample auto-radiograph (α particles)
  - Beam non-uniformities
  - Multi-actinide targets

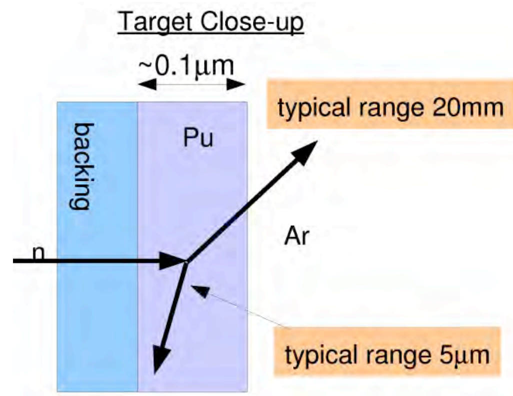


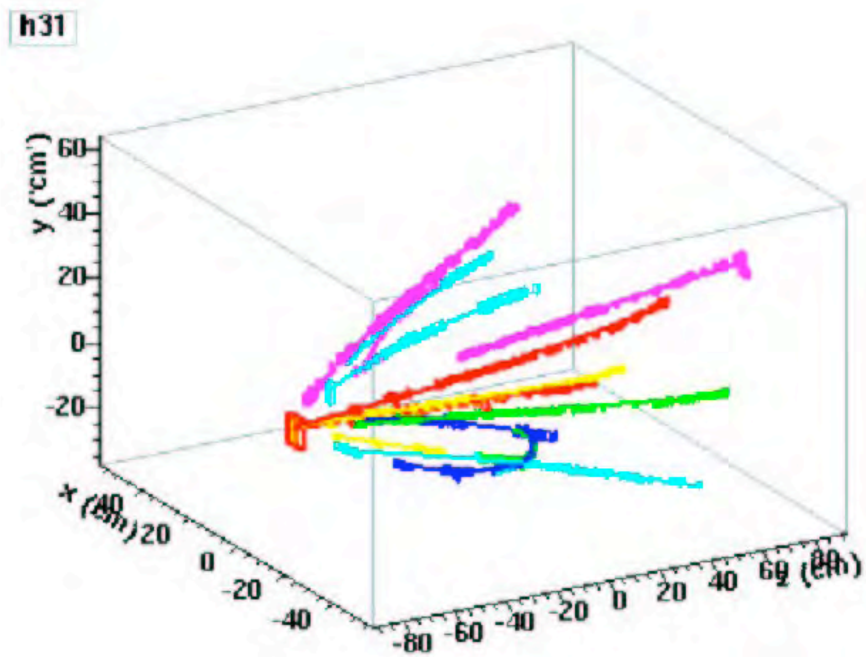
Time Projection Chamber

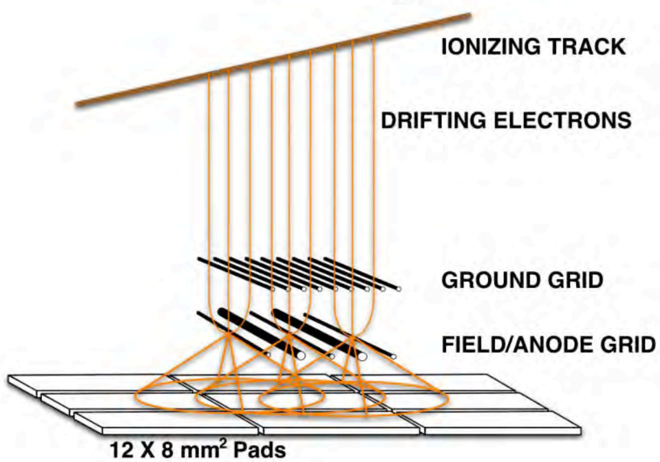
- Originally designed for high-energy physics experiments
- Take snapshots in time of ionization tracks in a fill ionization tracks in the fill gas

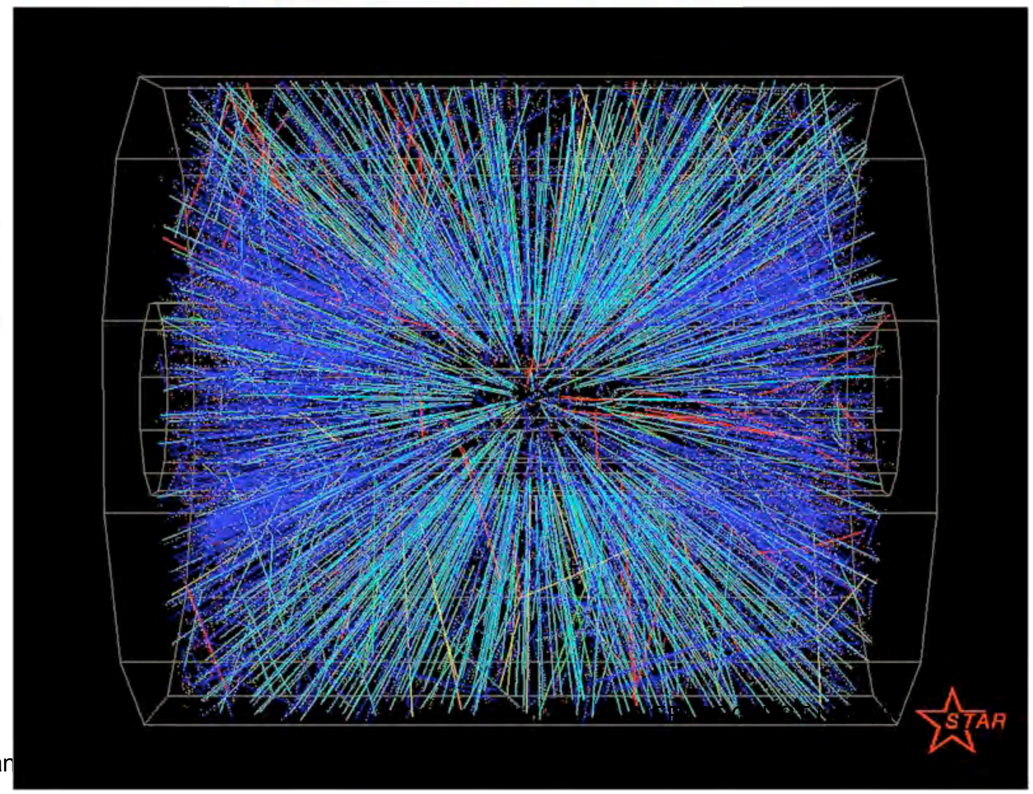


How the TPC Works







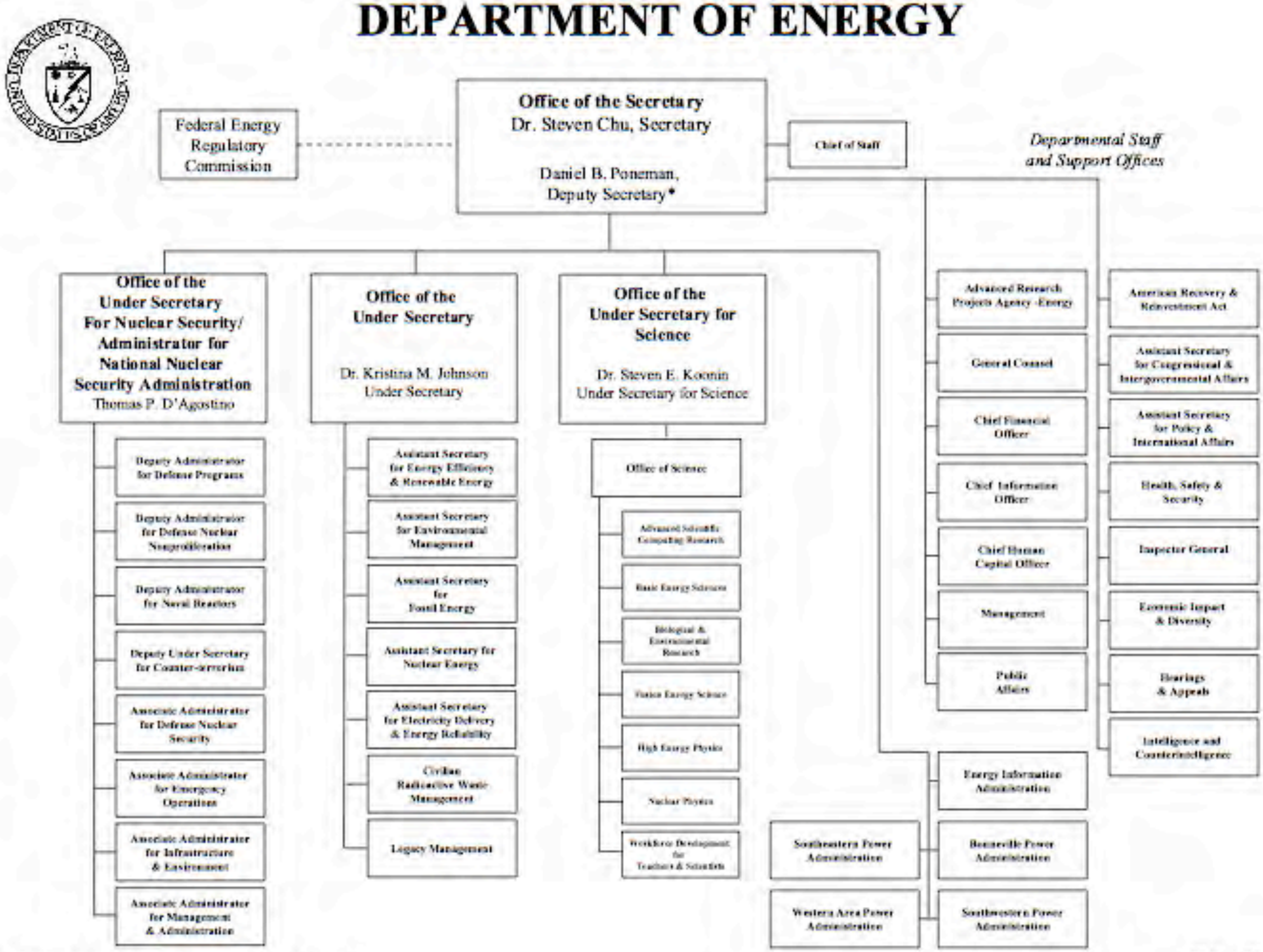


LBNL an

Project Participants
NIFFTE Consortia

- **The Neutron Induced Fission Fragment Tracking Experiment (NIFFTE) Consortium**
- **6 Universities and 3 National Labs**
  - Universities funded through NERI-funds
  - National Labs funded through NNSA and AFCI funds

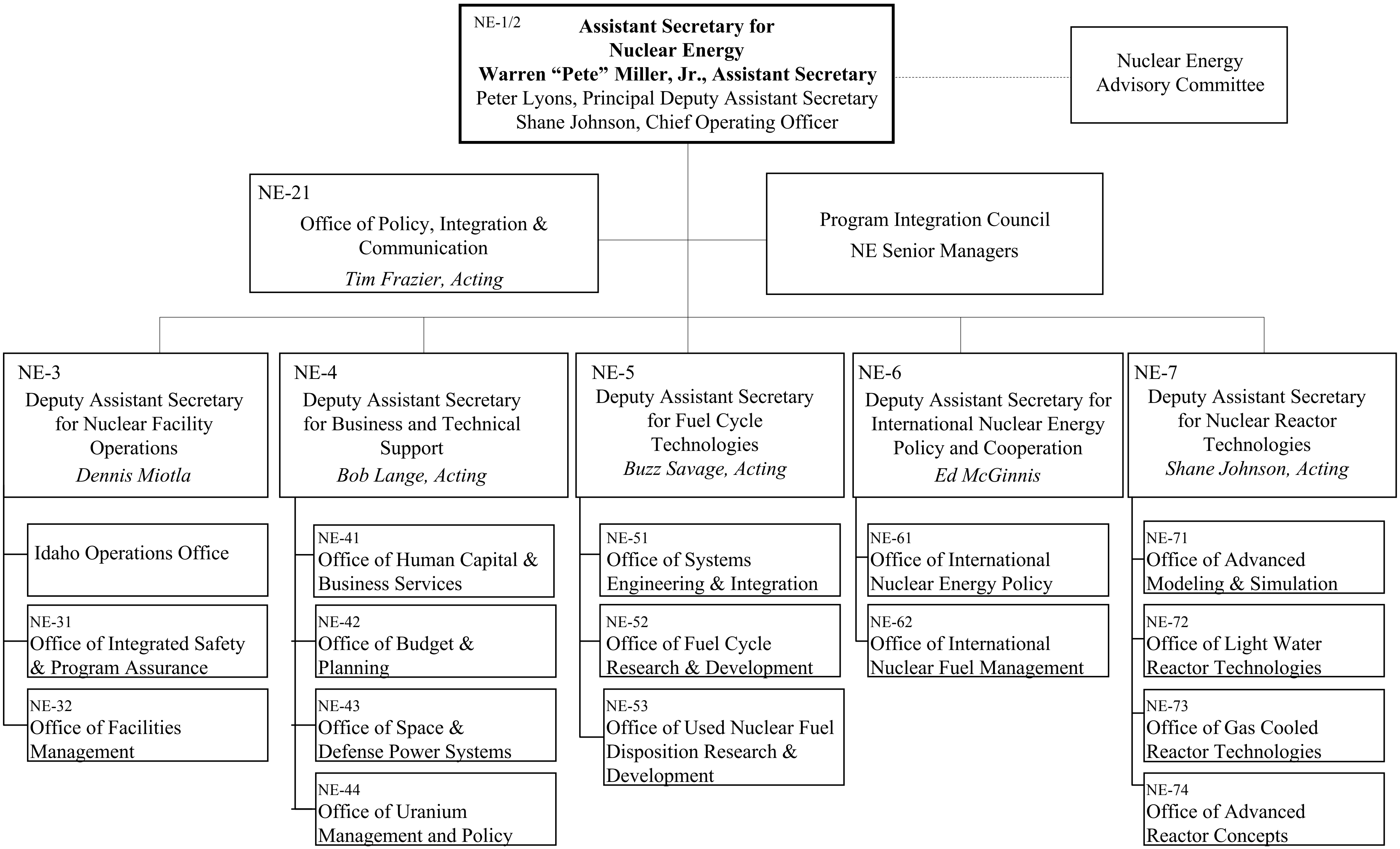
DEPARTMENT OF ENERGY



* The Deputy Secretary also serves as the Chief Operating Officer

30 Nov 09

Reorganization of the Office of Nuclear Energy



SC Supports Research at More than 300 Institutions Across the U.S.

The Office of Science supports:

- 27,000 Ph.D.s, graduate students, undergraduates, engineers, and technicians
- 26,000 users of open-access facilities
- 300 leading academic institutions
- 17 DOE laboratories

U.S. DEPARTMENT OF ENERGY | Office of Science

4

Summary

- NE R&D Roadmap issued
- R&D Objective Implementation Plans under development
- NE R&D program focused on long-term, goal oriented R&D with technology demonstrations decades away
- Excitement over Small Modular Reactors
- Possibility of cross-cutting R&D initiatives
- Increased international collaboration and cooperation
- Blue Ribbon Commission up and running to help determine options for future nuclear fuel cycles and disposition of high level waste

BACKUP SLIDES

January 29, 2010: Blue Ribbon Commission Announced

- Obama Administration decided last year that Yucca Mountain was not a viable alternative for geologic disposal of used nuclear fuel
- Secretary Chu announced the formation of a 15-person commission to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle
- Co-chaired by former Congressman Lee Hamilton and former National Security Advisor Brent Scowcroft
- The Commission will provide recommendations for developing a safe, long-term solution to managing the nation's used nuclear fuel and nuclear waste
- Commission will produce an interim report in 18 months, and a final report no later than 24 months; first meeting was March 25-26; second May 25-26
- The Obama administration announced that it would withdraw the Yucca Mountain license from the NRC "with prejudice"
- Legality of withdrawal is under judicial review
- DOE is planning to close out the Yucca Mountain program by Sep. 30 and transition functions to NE

Secretary of Energy Steven Chu